Hematologic effects of the high-energy endocardial ablation technique

P. M. HOLT, M.D., M.R.C.P., AND E. G. C. A. BOYD, PH.D., M.INST.P.

ABSTRACT  Ablation of atrioventricular conduction is now widely accepted in the management of supraventricular arrhythmias. Reports of high temperatures, high pressures, and gas production suggest that there may be adverse effects on the blood, the electrode, and the cardiovascular system. In this investigation, using samples of fresh, heparinized pig blood, we measured hemolytic damage, the liberated gas volume and composition, and electrode erosion associated with high-energy electrical ablation. The blood was tested in a 10 liter tank at room temperature. Impulses of 10 to 400 J were applied to new USCI No. 6F bipolar pacing electrodes using both positive and negative polarities. Voltage and current waveforms were recorded. The volume of gas liberated with cathodal electrodes was 0.50 μl/J up to 50 J and 0.29 μl/J above 100 J. It was composed predominantly of hydrogen and nitrogen, with carbon dioxide and oxygen. With positive electrodes, the gas volume was linearly related to energy at 4.34 μl/J up to 200 J and also contained carbon monoxide. The hemolysis was directly proportional to impulse energy for both cathodal and anodal electrodes, being 1.37 μl/J and 4.48 μl/J, respectively. Electrode erosion was substantial but clinically acceptable. We conclude that there are marked differences in the energy conversion processes and, where the same energy can achieve a comparable clinical effectiveness, there are advantages in using a cathodal electrode polarity.

It is also advisable to use lower energies.

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ABLA TION of atrioventricular conduction by means of high energy delivered via standard pacing catheter electrodes has become an accepted technique in the management of supraventricular arrhythmias in man.1-4 Early reports of this technique revealed the production of low x-ray density material near the electrode tip immediately after the delivery of the electrical impulse. Gas production was confirmed by tank experiments in vitro5 using video recordings and high-speed cine film. These tests also indicated that temperatures in excess of 1700°C were generated at the electrode surface together with very high pressure pulses. Such temperatures and pressures were likely to cause significant blood damage. A pilot study using a limited volume of fresh human blood6 showed the gas released by cathodal impulses to be composed of hydrogen, oxygen, and nitrogen with significant red cell hemolysis. Reproduction of these effects in vivo may render the extension of the high-energy ablation technique to left ventricular arrhythmic foci7-8 potentially hazardous.

The aim of this study was to investigate the hematologic effects of high-energy impulses, both anodal and cathodal, to assess red cell injury and the potential risk from gas emboli.

Materials and methods

The investigation was carried out in a rectangular 10 liter plastic tank, approximately 22 × 17 × 28 cm partially filled with 7 liters of blood. A back paddle from a standard defibrillator was submerged in the blood and clamped to the side wall of the tank. The tank also contained a mixing paddle. This consisted of a horizontal rectangular acrylic sheet approximately 5 cm smaller than the plan section of the tank, with vertical plastic rods attached at diagonally opposite corners.

Any gas produced was collected in the central assembly of the apparatus (figure 1). This was composed of a 12.5 cm diameter inverted plastic funnel attached to a round-bottomed polycarbonate centrifuge tube. A plastic crossbar mounted across the mouth of the funnel was used to position the catheter electrode under examination. A length of plastic manometer tubing was inserted through a second hole in the crossbar, passed into the funnel to the end of the round-bottomed tube, and then secured to the crossbar. This was the gas collection assembly. A vibration generating device operating at twice power line frequency was applied to the external surfaces of the collecting apparatus to dislodge any adherent gas bubbles.

A junction box was used to connect the defibrillator to the electrodes in the tank and to the recording instrumentation. It
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FIGURE 1. Diagram of the tank (A) and the gas collection assembly (B) with the support crossbar (C) used during delivery of high-energy impulses to 7 liters of fresh pig blood. The defibrillator back paddle (D), the electrode (E), the mixing paddle (F), and the gas sampling glass syringe (G) are shown.

contained a potential divider to reduce the high voltage to a level suitable for recording and series resistors for converting the system current flow into voltage.

Gas samples were collected by aspiration through the manometer tubing into 10 ml glass syringes, and the samples required for hemolytic determinations were taken in 10 ml disposable plastic syringes.

Analyses of the gas samples for nitrogen, oxygen, hydrogen, carbon monoxide, and carbon dioxide were performed by British Oxygen Corp., Analytical Services Department, with a gas chromatograph fitted with a thermal conductivity detector and a molecular sieve 5A column, with argon as the carrier gas. Carbon dioxide analyses were carried out on a similar instrument with a Porapak Q column and helium carrier gas. Suitable standards were prepared by means of a set of Wosthoff gas blending pumps. Hemolysis was measured by optical absorption at wave lengths of 541 and 577 nm on a Pye Unicam SP1805 Ultraviolet spectrophotometer. The electrical signals were recorded on a Racal Store 7 instrumentation tape recorder. A Siemens Mingo graph 34 chart recorder was used for playback. The defibrillator was calibrated for energy delivered into a 50 Q load by a Simonsen and Weels EM-1 energy meter and also by direct measurements of capacitor value and voltage. Platinum assays were performed by neutron activation analysis and micrographs were taken with a Hitachi HU12A electron microscope and an SS20 scanning unit.

Before the formal study, several experiments were conducted to test the feasibility of the protocol, the integrity of the apparatus, and the logistics involved in the blood collection and gas analysis.

The method consisted of four distinct sections: (1) the preexperimental preparation of the apparatus and the blood samples, (2) the application of impulses to the 7 liter blood volumes, (3) a concurrent hemolysis experiment, and (4) the additional measurements. These are described in detail below.

Preexperimen t preparation. Before each experiment, the following procedure was adopted. Fresh pig blood was collected in 7 liter quantities, heparinized with 20,000 U liter, and stored overnight at 4° C. It was then warmed gently to 20° to 25° C before the test on the following day.

A new No. 6F bipolar USC1 catheter electrode was inserted through the retaining hole in the crossbar until both the proximal and distal electrodes were within the volume of the funnel. The gas collection assembly was lowered into the tank until the funnel rim was 5 cm below the blood surface. The air in the gas collection assembly was aspirated manually until it was entirely filled with blood. After the use of the vibration device, a further 50 ml of blood was withdrawn to remove any remaining small bubbles, in addition to the blood at the top of the tube, which may have been red cell-depleted because of gravitational settling. This blood was returned to the tank.

Experiments. Four different experiments were conducted with fresh pig blood for each, and different sequences of impulse energies. These are described below: (1) Impulses were applied with the electrode tip negative with respect to the back paddle, in an ascending magnitude of 10, 25, 50, 100, 200, and 400 J. A total of 4000 J was delivered at each impulse energy. (2) Impulses were applied as in (1) above with the electrode tip negative with respect to the back paddle, in a descending energy order. (3) Impulses were applied with the electrode tip positive with respect to the back paddle, in an ascending magnitude of 10, 25, 50, 100, and 200 J. A total of 4000 J was delivered at each impulse energy. At the end of this sequence the electrode polarity was reversed and 10 and 400 J impulses were applied. (4) Impulses were applied with the electrode tip positive with respect to the back paddle as in (3) above, in a descending energy order.

During the delivery of a particular impulse energy, e.g., 10 J, the following procedure was adopted: The distal electrode of a No. 6F bipolar USC1 electrode was attached to the appropriate output of the junction box and the requisite number of shocks, e.g., 400, was delivered to give a total of 4000 J. This took approximately 15 min. After the last impulse had been delivered, the vibration device was applied to the gas collection assembly. Four minutes later the gas in the tube head space was aspirated slowly into a glass syringe, together with sufficient blood to completely fill the remaining space in the 10 ml syringe. This was used as a temporary seal before capping the syringes. Where the volume was in excess of approximately 7 ml, more syringes were used. The blood in the top of the gas collection assembly was then ejected back into the tank and stirred with the mixing paddle for approximately 1 min. A 10 ml sample was taken in a disposable syringe for hemolytic assessment and examination of blood film. The next impulse energy in the sequence was then selected and 4000 J was delivered by the procedure described above.

The volumes of gas in the syringes were measured three times: immediately after aspiration, approximately 15 min later, and just before analysis. The two initial measurements were complicated by the presence of foam at the gas-liquid interface. The gas analysis was conducted within 2 hr of the end of the test sequence.

Hemolytic samples were centrifuged within 1 hr of the end of the experiment. Initially, the heparinized pig blood in the tank had been carefully mixed and two 10 ml samples were taken. One was completely hemolyzed by dilution with 99 parts of water as a 1% calibration specimen, while the second gave the starting level of hemolysis for the blood in the tank.

The electrodes were connected cathodally in experiments (1) and (2) and anodally in experiments (3) and (4). All experi-
mments, were performed three times, thus using a total of 12, 7 liter quantities of fresh pig blood and 12 new USCI No. 6F bipolar electrodes.

After the delivery of the planned sequence of energies in experiments (3) and (4), the electrode polarity was reversed by connection to the cathodal output of the defibrillator. Representative 4000 J total deliveries were performed at low and high impulse energies and gas and hemolysis samples were taken for comparison with the results obtained in experiments (1) and (2).

**Concurrent experiment.** Before main experiment (1), twice the quantity of fresh blood was collected. The two 7 liter volumes were gently blended and half was used for the main experiment and the other half used in an identical second apparatus. During the course of the main experiment, a concurrent experiment in the second apparatus was performed. The mixing and aspiration were conducted in an identical manner and at the same time as the main experiment. No impulses were delivered and no gas was produced or collected, but all samples for hemolytic analysis were taken, centrifuged, and analyzed at the same time as the experimental samples.

**Additional measurements.** During the course of the gas and hemolytic experiments, three voltage and current recordings were made at each energy and for both polarities of electrode. Photographs were taken of two electrodes before and after 48,000 J. Scanning electron micrographs were taken at 40× and 400× magnification. Blood samples were taken for platinum assay.

**Results**

The mean hemoglobin concentration of the pig blood was 12.4 to 13.4 g/dl (mean 13.14, SD 0.12 g/dl). During the delivery of high energy impulses to the blood, gas was produced and hemolysis occurred. These effects are considered separately below.

**Gas production.** The gas sample syringes contained gas, foam, and blood. The immediate and 15 min volumes were measured from the foam-liquid interface. These volumes were averaged with the volumes recorded just before analysis. The latter volumes were not significantly different from the initial two measurements.

When 4000 J was delivered as impulses ranging from 10 to 400 J to fresh, heparinized pig blood by means of a cathodally connected electrode, the volume of gas collected ranged from 2.96 to 0.86 ml, respectively. The volumes collected are shown in table 1. Mean energies of 400 J are frequently used in clinical ablation procedures; therefore the gas volume produced per 400 J was calculated and these results are illustrated in figure 2, A. The volume of gas liberated per single impulse is plotted against impulse energy in figure 2, B. The mean gas production rate over the impulse range 10 to 50 J was 0.50 μl/J, falling to 0.29 μl/J in the higher energy range of 100 to 400 J.

Analysis of the gas samples showed that they consisted predominantly of hydrogen and nitrogen with lower levels of oxygen and carbon dioxide. Traces of methane were detected. The mean values are given in table 1. As the impulse energy rose, the percentages of hydrogen and carbon dioxide fell and the nitrogen and oxygen content rose.

Details of the gas produced via anodally connected electrodes (experiments [3] and [4]) are given in table 2 and the volumes are illustrated in figure 2. No data were available for energies over 200 J, since the apparatus could not withstand 400 J delivered anodally. The gas volume produced per impulse increased linearly from 10 to 200 J at a rate of about 4.34 μl/J. The gas liberated, in addition to the constituents found with cathodal electrodes, contained approximately 5% carbon monoxide. Traces of methane and acetylene or ethane were detected in several samples. The analysis apparatus was equally sensitive to the latter two gases. The percentages of these gases varied only slightly with energy.

**Hemolysis.** With either electrode polarity, hemolysis was found to be directly proportional to impulse energy. The volume hemolyzed per 400 J delivered at each energy is shown in figure 3, A. Expressed as blood hemolyzed per joule delivered, the rates were 1.37 μl/J for cathodal electrodes and 4.48 μl/J for anodal electrodes, as shown in figure 3, B.

The results from the concurrent hemolytic experiment, in which blood was stirred and aspirated but not subjected to impulses, showed only a slight increase in hemolysis during the time of the experiment, ranging from 0.0231% at the start to 0.0239% at termination. These results were obtained by least-squares linear
regression analysis of the data. The standard deviation was 0.00079%.

Analyses of the blood films after the experiments showed evidence of cellular clumping and aggregation. There was no significant change in hematocrit or hemoglobin.

Electrode erosion. Immediate observation of the electrodes after a total delivery of 48,000 J showed considerable erosion, with a completely different surface appearance. The cathodally connected electrode had an overall dull finish, similar to a shot-blasted surface. The anodal electrode had bright, shining, circular areas that appeared very smooth. The scanning electron micrographs (figure 4) confirmed this impression and showed that both electrode surfaces had fused. The cathodal electrode had a "splashed" appearance. The circular anodal electrode areas had a flattened lavalike appearance with concentric undulations. Within most of the circular areas there were one or two deep cavities. The platinum assay results showed that for 20,000 J delivered, there were increases in blood platinum levels of 0.42 and 0.12 µg/ml for cathodal and anodal electrodes, respectively. This indicated total electrode platinum losses of 2.94 and 0.84 mg.

Current and voltage. The current and voltage records for both polarities are shown in figure 5 for impulse energies of 10, 50, and 200 J. The peak values of voltage and current for the anodal electrode are on average slightly higher than those for the cathodal electrode. The salient difference was the pronounced peak in the voltage graphs, which moved progressively earlier in the waveform as the energy was increased. The rate of rise of voltage for the 200 J anodal impulse was extremely steep at 4000 V/msec and was maintained to the peak voltage. The cathodal electrode graph, in contrast, showed a much smoother waveform.

Discussion

Preparations in vitro should replicate the clinical situation as closely as practicable if they are to provide useful data that can be extrapolated to the situation in vivo. Freshly collected pig blood was used because such large volumes of human blood were not available. Time-expired blood bank material was considered inadequate because hemolysis and natural degradation would be unknown factors possibly affecting the electrical discharge, the induced hemolysis, and gas composition. Similar denaturing would occur if the relatively long experimentation were conducted at 37° C. The investigation was therefore performed at room temperature.

It is known that the electrical conductivity of blood is approximately three times higher than that of cardiac muscle and more than 10 times higher than that of lung

<table>
<thead>
<tr>
<th>Number × energy</th>
<th>Mean volume (ml)</th>
<th>O₂</th>
<th>N₂</th>
<th>H₂</th>
<th>CO₂</th>
<th>CO</th>
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<tbody>
<tr>
<td>20 × 200 J</td>
<td>16.38</td>
<td>3.95</td>
<td>16.00</td>
<td>66.17</td>
<td>6.13</td>
<td>5.76</td>
</tr>
<tr>
<td>(1.09)</td>
<td>(0.71)</td>
<td>(1.50)</td>
<td>(0.01)</td>
<td>1.83</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40 × 100 J</td>
<td>18.26</td>
<td>3.51</td>
<td>15.91</td>
<td>66.96</td>
<td>5.99</td>
<td>5.62</td>
</tr>
<tr>
<td>(1.53)</td>
<td>(3.03)</td>
<td>(0.80)</td>
<td>(0.23)</td>
<td>0.64</td>
<td></td>
<td></td>
</tr>
<tr>
<td>80 × 50 J</td>
<td>16.26</td>
<td>3.46</td>
<td>17.20</td>
<td>66.83</td>
<td>6.57</td>
<td>3.95</td>
</tr>
<tr>
<td>(0.91)</td>
<td>(0.50)</td>
<td>(1.52)</td>
<td>(0.25)</td>
<td>0.66</td>
<td></td>
<td></td>
</tr>
<tr>
<td>160 × 25 J</td>
<td>17.64</td>
<td>3.16</td>
<td>13.50</td>
<td>69.39</td>
<td>6.08</td>
<td>5.10</td>
</tr>
<tr>
<td>(1.06)</td>
<td>(1.00)</td>
<td>(0.11)</td>
<td>(0.60)</td>
<td>0.41</td>
<td></td>
<td></td>
</tr>
<tr>
<td>400 × 10 J</td>
<td>18.24</td>
<td>2.86</td>
<td>11.77</td>
<td>68.43</td>
<td>6.50</td>
<td>8.12</td>
</tr>
<tr>
<td>(0.58)</td>
<td>(0.86)</td>
<td>(1.55)</td>
<td>(2.69)</td>
<td>1.07</td>
<td>0.52</td>
<td></td>
</tr>
</tbody>
</table>

See table 1 for notes.
tissue. For the combination of a small and a large electrode widely spaced in an infinite homogeneous conducting medium, 90% of the overall interelectrode impedance is controlled by the medium within a volume of 10 electrode radii of the small electrode. Comparing the effective electrode radius and the ventricular volume, we believe that the interelectrode impedance in vivo would be influenced by the ventricular blood conductivity. The thoracic tissue outside the heart would contribute a comparable proportion to the overall impedance. When filled with pig blood, the tank gave current values similar to our measurements in patients.

Because the interelectrode impedance is highly nonlinear, the defibrillator internal inductance and resistance must be considered as part of the load circuit. The energies quoted in this investigation are the energies stored in the capacitor and presented to the total circuit. The electrodes (both the intracardiac and the back paddle), the measurement system, and the defibrillator were identical to the system used for clinical ablation in our catheter laboratory. Thus the bench tests described in this investigation closely resemble, except for temperature, the situation in vivo.

Results from the preliminary studies showed little deterioration of the 7 liter blood volumes during over night storage at 4°C; this allowed refinement of the apparatus to enable it to endure repeated sequences of energy deliveries. The main investigation was limited to 200 J anodal impulses because of the violent turbulence in the blood volume, which produced significant loss of blood from the tank at higher anodal deliveries. Cathodal shocks of 400 J were contained satisfactorily.

The volume of gas required for accurate measurement and analysis was approximately 1 ml; therefore, the effects of multiple shocks were studied because the quantity of gas produced by most single impulses was insufficient. It was necessary to choose either (1) delivery of a constant number of shocks with variable total energy or (2) delivery of a constant cumulative energy with a variable number of shocks. For energies of 10 J delivered cathodally, over 100 shocks had to be delivered to produce a 1 ml gas sample, the minimum required for analysis. Therefore, if the same number of shocks were to be used, 100 shocks would be necessary at 400 J. This protocol could lead to several difficulties. Problems would have occurred with the catheter electrode and the defibrillator. The gas volume produced by anodal impulses would have been 82 ml with almost the same volume of hemolysis. This large gas volume would present sampling problems, and the gross level of hemolysis would necessitate a considerable increase in the volume of blood required, with the problems of interbatch variability. Constant cumulative energy and a variable number of shocks minimizes these difficulties and yields manageable gas and hemolysis volumes. Either method is open to criticism if there is a variation in gas production or hemolysis from impulse to impulse at constant energy. Delivering the energy in ascending or descending impulse magnitude showed only minor differences in the gas volume, composition, or hemolytic damage at any particular energy, suggesting no significant variation in effects from impulse to impulse. Although electrode erosion was substantial, it did not appear to be a significant factor affecting the mechanism of gas generation during the course of the experiment.

The total blood volume in the tank fell during the course of any single experiment due to the removal of samples for assessment of hemolysis and gas analysis. However, the cumulative volume lost was no more than 140 ml, which represented a 2% volume.

FIGURE 3. Hemolysis occurring in 7 liters of fresh pig blood per 400 J delivered at various impulse energies. The dots represent mean values and bars the standard errors of the means. A. Hemolysis per single high-energy impulse. The quantity of blood hemolyzed rises as the energy of the shock rises from 10 to 400 J.
loss. This was small compared with the errors from other sources, as indicated by the standard errors in the data. The gas composition was determined at the same time, allowing a comparative assessment to be made between differences caused by polarity and energy.

Assessment of the accuracy of the final hemolytic values is complicated by the variety of possible sources of error, e.g., the blood mixing, the sampling, the dilution of the plasma, and the spectrophotometer. The regression calculations in the concurrent experiment with 24 optical absorbance measurements gave a standard deviation of approximately 8 ppm from the best fit least-squares line. With 3 SDs to cover 99.7% of the experimental values, it is presumed that the differences in hemolysis reported for each impulse energy have uncertainties of approximately 50 ppm. Since the increase in hemolysis produced by any one impulse energy level was found to be no less than 500 ppm, this uncertainty is less than 10% in the reported hemolysis values.

FIGURE 4. Scanning electron micrographs of a USCI No. 6F electrode after delivery of 48,000 J as unipolar shocks via the distal electrode. Top panels, Effect produced when the catheter was connected to the cathodal output of the defibrillator. Bottom panels, Effect produced when the catheter was connected to the anodal output of the defibrillator.
The results of delivering the energy anodally differed markedly from the cathodal results. This suggests that there are two different energy conversion processes, as indicated by six observations made during this investigation. First, there was a large disparity in gas production, ranging from 0.29 to 0.50 μl/J for cathodal energy impulses and 4.34 μl/J for anodal impulses. Gas production was therefore 8.7 to 15.0 times greater with anodal energy delivery. Second, energy delivered via anodal electrodes produced hemolysis three times higher than that produced by cathodal electrodes. Third, the mechanical pressure or shock wave was subjectively larger because 400 J could not be used with anodal polarity in the test tank. Fourth, carbon monoxide was produced in significant quantities with positive electrodes, an average of 5.7%, and none was produced with negative electrodes. Fifth, the current and voltage waveforms were different; the higher energy anodal voltage leading edge was almost linear to the peak voltage. Finally, there was a marked variation in the surface erosion of the electrodes as shown by the scanning electron micrographs in figure 4. These effects on hemolysis, gas, and pressure suggest that lower energies delivered via a cathodal electrode are preferable for endocardial ablation procedures.

The composition of the gas produced is probably the result of many factors. The nitrogen found in the collected gas could have been released from the plasma by liquid vaporization or mechanical shock wave negative pressures some distance from the electrode surface. Subatmospheric pressures have been previously reported\(^9\) after the initial positive-pressure pulse. The oxygen/nitrogen ratio is lower than the ratio in solution. This is the case for both polarities and it may have been caused by absorption of the oxygen by the hemoglobin.

Faraday's law of electrolysis predicts the formation of hydrogen around a negative electrode. From the charge transported per impulse, we calculated that the volume of hydrogen evolved would be 2.1 to 13.2 μl for 10 to 400 J impulses. The amount detected was 5.1 to 43.1 μl, respectively. An alternating current flow could produce extra hydrogen. However, the current-time curves show that there is insufficient current reversal to account for this discrepancy (see figure 5).

Similarly, there should be no hydrogen produced with a positive electrode unless the current reverses during the impulse. Figure 5 shows that although there was some reversal, there was an insufficient current-time integral to explain the much larger volumes of 31.2 to 542 μl over the range 10 to 200 J.
It is therefore necessary to find another mechanism that could lead to the generation of hydrogen. The presence of electrical plasmas within the “fireball” around the electrode has been proposed to explain the optical emission and electrode surface fusion. Plasma temperatures may be high enough to promote thermal dissociation of water releasing hydrogen, oxygen, and various species of free radicals. However, the oxygen is likely to be in the highly reactive nascent form, and it is expected that it could cause severe oxidation of the biological molecules before it can be absorbed by the hemoglobin. This reactive oxygen would be released only after the establishment of the electrical plasma, i.e., when the “fireball” has formed. With an anodal electrode, however, the oxygen produced initially by electrolysis would be available immediately for the oxidation of any biological material nearby before the “fireball” has formed. The heat of reaction of this anodal process would increase the local environmental temperature around the electrode and enhance the initial energy dissipation. This effect could account for the more violent effects observed when anodal electrodes were used.

The surface appearance of the electrodes suggests that the plasma discharges were different for the two electrode polarities. The anodal electrode surface appeared to have a relatively small number of discrete foci, suggesting a small number of stable arc initiation points. The eroded cathodal electrode showed a more uniform surface appearance, which suggests a “sheet” type of discharge mechanism. The significance of these observations warrants further attention. The rate of erosion and the absolute erosion values also require further investigation.

Although carbon monoxide was produced during anodal discharges, the maximum volume produced was 0.16 ml for 400 J (40 × 10 J). The volume produced for single shocks of 10 to 200 J was below that producing clinical toxicity. Similarly, the quantity of platinum released from the electrodes by the energy used in regular ablation procedures was not clinically significant.

The duration of each experiment rendered heparinization mandatory and therefore no assessment of thrombogenesis could be made. However, the volume of gas produced experimentally during anodal deliveries may prove to be a potential source of emboli. This would be important in procedures involving the left ventricle.

The effects of cathodal and anodal polarity were compared because both polarities have been successfully used in clinical ablation procedures. However, the increased hemolysis and gas formation and, more importantly, the greater shock waves produced with positive electrode polarity make cathodal energy delivery preferable.

In conclusion, this investigation with anodal and cathodal electrode polarities has shown that (1) there are two different energy conversion processes involved and (2) hemolysis and gas production are considerably reduced with cathodal electrode polarities and lower impulse energies.

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